CHARACTERISTICS OF AEOLIAN GRAIN TRANSPORT OVER A FLUVIO-GLACIAL LACUSTRINE BRAID DELTA, LAKE TEKAPO, NEW ZEALAND

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ABSTRACT

This paper presents results from one of the few scientific studies to examine the physical characteristics of aeolian sediment transport in an alpine area, where topographically reinforced *foehn* winds initiate dust storm events. The major objective of this study is to improve knowledge of aeolian processes in mid-latitude alpine regions experiencing extreme wind speeds. Of particular interest is the role of surface characteristics in contributing to the unusually deep saltation layer which is seen to form over fluvio-glacial deposits in the Southern Alps of New Zealand. Sediment was collected at several heights (0·5, 1, 2 and 4 m) and locations over a large alpine braided river delta, and standard laboratory techniques used to examine grain size characteristics. An image processing technique was also used to evaluate grain roundness.

Grains filtered from the airstream at 0·5 m and 1 m above such surfaces were found to display a mean grain size of approximately 300 to 435 μm, resembling grain size characteristics of saltation clouds previously observed in high latitude, cold climate locations, in contrast to desert and prairie environments. Samples collected at 2 and 4 m above the surface were found to consist of 60 to 65 per cent sand-sized material, with some grains exceeding 1–1·5 mm in diameter. Grain shape analysis conducted on silt- and clay-sized grains filtered from the airstream above mixed sand and gravel surfaces showed such grains to display an increase in grain roundness with height. This characteristic is thought to reflect the airstream's shape-sorting ability and has important implications with respect to the often observed increase in grain roundness in aeolian deposits with increasing distance from source areas. Namely, if more rounded grains are preferentially carried higher into the airstream and therefore into regions of higher wind speed, they should theoretically be transported further from the entrainment zone before being deposited.

The high wind speeds observed, often exceeding 30 m s^{-1}, are seen to transport significantly larger sediment than reported in the literature for desert and prairie environments. In addition, the mixture of grain sizes, and especially the pebble- and cobble-sized clasts that dominate the fluvio-glacial deposits associated with the braided rivers in this mountain region, also appear to increase significantly the trajectory height of saltating sand grains. As a result of these two factors, the depth of the saltation cloud often exceeds 1 m.

Observations made in this study therefore highlight the need for field and laboratory aeolian process studies to be extended to examine grain transport over coarse-grained beds during much higher wind velocities than typically reported in the literature. Such studies would provide a valuable insight into aeolian processes in high latitude/altitude environments, such as loess genesis. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Aeolian processes in the alpine environment have attracted relatively few detailed scientific investigations, as the more classic desert and prairie settings have been the primary focus of both historical and contemporary studies into the dynamics of fine grain transport by the airstream. Undoubtedly, close proximity of European and North American research institutions to the Sahara Desert and the Dust Bowl region of the mid-western United States of America, respectively, promoted many of the now classic studies into aeolian grain transport by Bagnold (1941), Chepil (1945a, b), Chepil and Woodruff (1957, 1963) and others. These early studies

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identified fundamental relationships and concepts governing sand and dust transport by the airstream which now form the basis for many contemporary investigations into aeolian sediment transport. Technological advances allowing the observation of fine grain transport by the airstream through the use of high technology wind tunnels (Nickling, 1988; Williams *et al*., 1990), in conjunction with computer simulations of fine grain transport, continue to advance the science. However, research into aeolian grain transport is still largely confined to the semi-arid/arid desert and prairie environments, such as that outlined by Jones *et al*. (1986), Lougeay *et al*. (1987), Brazel and Nickling (1987), Wheaton and Chakravarti (1990), Wheaton (1992) and Lee *et al*. (1993). Only limited observational studies of aeolian processes in alpine (or high latitude) environments have been undertaken, as reviewed by McKenna Neuman (1993). Consequently, there is a substantial lack of scientific literature on the physical nature of aeolian processes in such environments.

Aeolian processes in the alpine environment are subject to several controls which clearly distinguish them from similar processes in desert and lowland/prairie settings, including the influence of snow and ice on fine-grained sediments and the erosive potential of topographically reinforced winds. Such controls on aeolian processes in the alpine environment are typically seasonal. In the Southern Alps of New Zealand, the most favourable periods for aeolian sediment transport occur during early spring (September–October) and late autumn (April–May) when *foehn* or *chinook* type wind events are most frequently monitored.

As some of the processes operating in this exceptionally dynamic alpine environment differ from those observed elsewhere, it is anticipated that there will also be significant differences in the nature of aeolian sediment transport. For example, visual observations suggest that the occurrence of dust storms is more vigorous than in lower energy environments. Similarly, temporal controls on dust storm occurrence are expected to be unique to this environment.

Dust storm genesis in this region is mostly confined to the large braided rivers which drain eastern alpine catchments and the degraded tussock grasslands of the inner montane basins. Scientific research into aeolian processes in this environment has been limited, with only three publications on the subject (Butterfield, 1971; McGowan, 1996; McGowan *et al*., 1996). However, with the continued development of the inner montane basins and proglacial lakes of the Southern Alps for hydroelectric power generation and tourism, incidents of blowing dust and dust storms appear to be causing nuisance and hazards to visitors and residents of this region more often.

This paper aims to improve knowledge of the nature of aeolian sediment transport in a particularly dynamic alpine region, under the influence of a unique combination of environmental processes. These processes include snowmelt/fluvial, freeze–thaw and wind effects. Results are presented from the analysis of fine-grained sediment filtered from the airstream by passive samplers during dust storms over an exposed lacustrine braid delta at Lake Tekapo in the central Southern Alps of New Zealand. This hydro-lake was the site of severe dust storms experienced throughout the spring of 1989.

PHYSICAL SETTING

Lake Tekapo is situated approximately 180 km southwest of Christchurch in the central Southern Alps of the South Island, New Zealand (Figure 1). Local relief varies from relatively flat outwash surfaces and hummocky moraine deposits, to steep mountainous terrain with many peaks exceeding 2500 m. Lake Tekapo occupies a glacially excavated rock basin and has a surface area of approximately 87 km^2.

The largest tributary to flow into the lake is the Godley River, which enters Lake Tekapo via its northern shoreline forming the Godley River Delta (Figure 1). Annual estimates of the supply of sediment to this prograding braid delta are in excess of 440 000 m^3 (Kirk, 1989). The Godley Riverbed and associated delta are sparsely vegetated, primarily in response to high seasonal discharges and inundation, respectively.

The climate of the Lake Tekapo area is typical of the inner montane basins of the South Island, where elevation and rainshadow effects dominate in the relative absence of a maritime moderating influence on the weather. Rainfall at Tekapo Village (Figure 1) averages 600 mm per year resulting from an average of only 72 rain days (days on which 1 mm or more of rain is recorded), whereas near the headwaters of the lake catchment annual rainfall may exceed 5000 mm. During winter, snowfalls of 50 to 70 cm may be experienced at lake level,

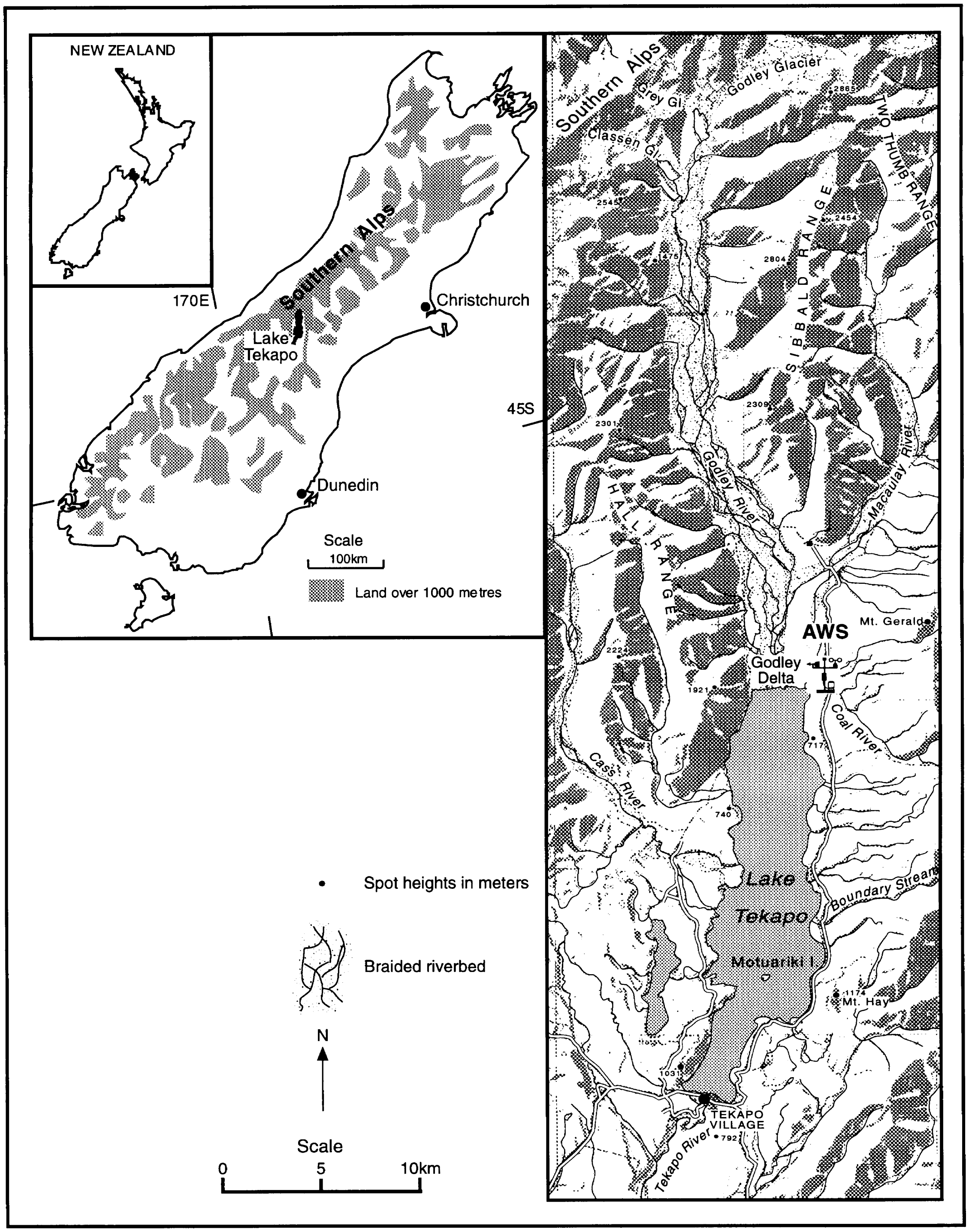

Figure 1. Location map of study area with places referred to in the text indicated

while numerous lighter falls may occur. Annual sunshine hours are in excess of 2200 h, while an average daily range in temperature of 11·6°C is experienced (Garr and Fitzharris, 1991).

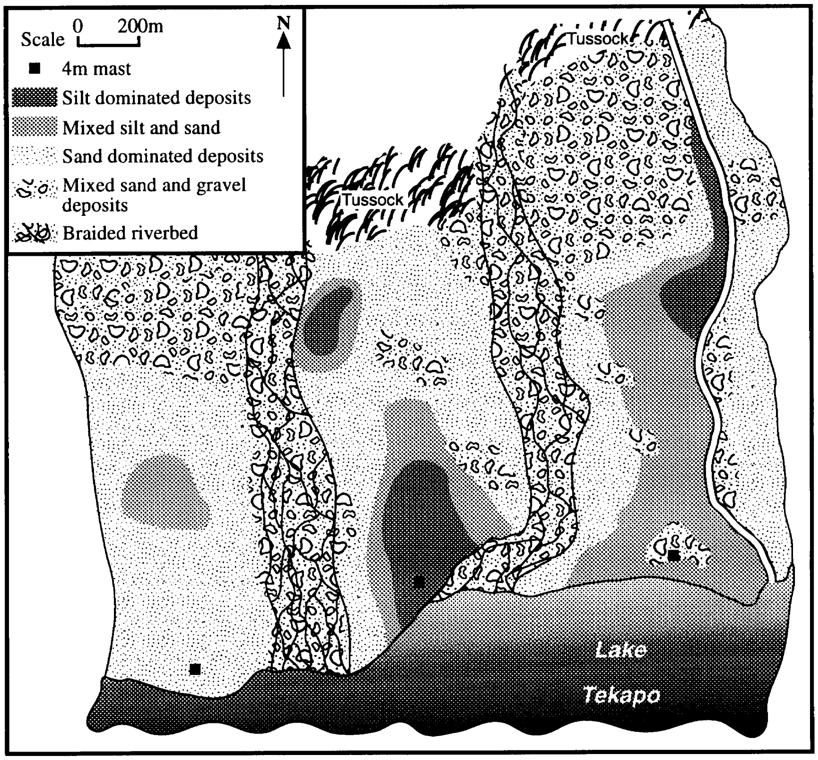

Figure 2. A schematic diagram of the sediments present on the exposed Godley River Delta and the approximate positions of the sediment sampling masts (September 1992)

The wind regime of the Lake Tekapo basin is dominated by light, diurnally reversible, thermally driven circulations, such as the locally generated lake–land breeze circulation (McGowan *et al*., 1995). Orographically generated *foehn* west to northwesterly winds, which are locally referred to as the ''*nor'wester*'', are the most common form of surface level gradient airflow experienced in the study area and provide ideal conditions for the initiation of aeolian processes, such as low humidities and warm gusty winds which may exceed 30 to $50\,m\,s^{-1}$ (McGowan and Sturman, 1996).

Local vegetation in the vicinity of the lake consists of tussock grassland on the lower slopes of the surrounding mountain ranges and the adjacent lowland areas. The quality of natural vegetation decreases dramatically along the north–south axis of the lake basin in response, primarily, to the strong north–south precipitation gradient within the catchment. Vegetation cover south and west of Lake Tekapo is severely depleted owing to overgrazing by sheep and a persistent rabbit infestation problem.

THE GODLEY DELTA

The Godley River Delta is acknowledged as a major source of wind-blown dust in the Lake Tekapo area when its topset beds are exposed to aerial processes (July–January) (Figure 2; McGowan, 1994). In general, the topset beds display a down-delta and cross-delta reduction in mean grain size from the point of entry onto the delta surface. Distal fining of surface sediments down the delta may result from a combination of processes. Firstly, a reduction in stream competence as the channel gradient decreases near the river mouth means that coarser sediments are deposited close to where the river begins to cross the deltaic surface. Secondly, saltating and creeping sand grains moving down-delta during strong downvalley northerly *foehn* winds will be deposited near the lakeshore upon contact with the moist deltaic surface, or on contact with water. Consequently,

prolonged low river flows (no recharge of deltaic fine sediments) result in a reduction in fines within the fluvioglacial deposits over the upper reaches of the delta. These surfaces therefore become stripped of fines (fine sand- and silt-sized grains) as prolonged deflation by the airstream produces deflation surfaces. Throughout the gradual lowering of the lake during late winter and early spring prior to spring inflows, aeolian deposition of sand grains migrates lakewards together with the principal source areas of such particulates.

Distal fining of surface sediments laterally on the delta results primarily from overbank type deposition during flood events. Close to the main channels, lobe-like longitudinal deposits diverge in a cross-delta pattern, with fines being deposited furthest from zones of highest velocity. This process appears to be the principal formative mechanism for the development of two extensive silt/clay deposits on the delta which support the capillary rise of water to their surface and consequently remain moist. As a result, the surfaces of these deposits were observed not to supply dust-sized material to the airstream, except where they made contact with the more porous coarse-grained alluvium (Figure 2). Along these contacts, the silt/clay deposits did become dry and were subject to deflation through ballistic impact processes associated with large saltating sand grains (McGowan, 1994).

The topset beds of the Godley Delta were also identified to be positively skewed (inclusive graphic skewness (Folk and Ward, 1957; Nolan, 1992)). This characteristic of sediments, as discussed by Friedman (1961, 1967), reflects the unidirectional nature of the transportation media that supply sediment to the delta, the Godley River and down valley *foehn* wind storms. Interseasonal fluctuations in the lake level, which result in the oscillation of the lake wave base over the delta, do not appear to influence markedly the sedimentological characteristics of the topset beds, based on results from this survey. However, aeolian processes operating on the exposed topset beds may have destroyed evidence of lacustrine processes prior to the collection of sediment samples for analysis, as suggested by Nolan (1992).

Situated on the western part of the Godley Delta is a large sandur; this appears to be semi-permanent in nature, based on the analysis of historical photographs of this location. It appears that two large, well vegetated inter-channel islands immediately upvalley from the sandur protect it from disturbance by migrating stream channels, except during large flood events. Numerous classic aeolian features were identified on the surface of the sandur, such as megaripples and small barchanoid dunes with relief between 0·5 m and 1·10 m. Smaller scale adhesion ripples, sand tails and nebkhas are additional common aeolian features of this highly dynamic region (Figure 3).

AEOLIAN SAND AND DUST TRANSPORT

Observation techniques

The extremely harsh and dynamic nature of the field area introduced a number of constraints on the collection of wind-blown sediments. For example, large areas of quicksand on the delta meant that all monitoring equipment used had to be (i) installed manually, (ii) robust in construction so as to withstand severe sand blasting during wind storms, (iii) self-contained, and (iv) cheap to produce, as the loss of equipment due to flooding was an ever-present risk. With these limitations, passive sediment traps similar to those designed by Butterfield (1971) were used (Figure 4). These consisted of a PVC drainpipe T-joint 265 mm in length, with a 60 mm diameter orifice. A perspex fin attached to the rear of the trap enabled it to be self-orientating into the airstream, while a detachable clear sample jar suspended below collected particles filtered from the airstream by an internal gauze filter with a mesh size of 212 μm (Figure 4). Traps of this design were tested by Butterfield (1971) and found to be 92 per cent efficient for wind speeds less than 15 m s^{-1}. Traps were attached to 4 m masts at vertical intervals of 0·5 m, 1 m, 2 m and 4 m, corresponding to the logarithmic wind profile expected above the relatively uniform deltaic surface. The traps were serviced during regular visits to the field area and were relocated during these visits in response to lake level fluctuations, so that they remained within approximately 150 m of the shoreline (Figure 2). Some traps were deployed with 77 μm mesh filters to determine if fines were being blown through the 212 μm mesh filters used in the majority of traps. However, no statistically significant difference was found between the grain size statistics of the samples collected by the two types of trap,

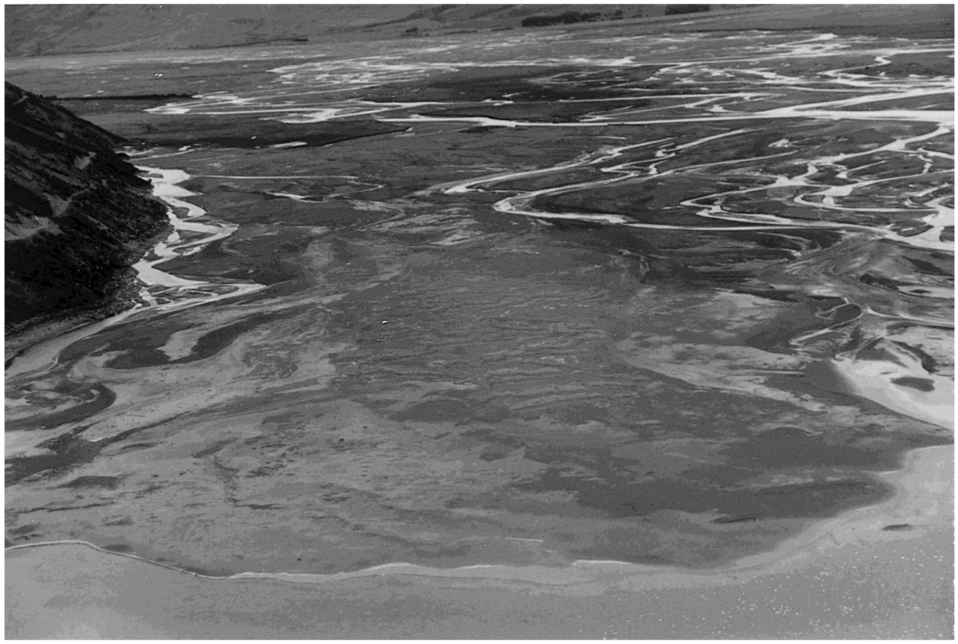

Figure 3. An aerial view of the large sandur located on the western Godley River Delta (note the megaripples in the centre of the photograph)

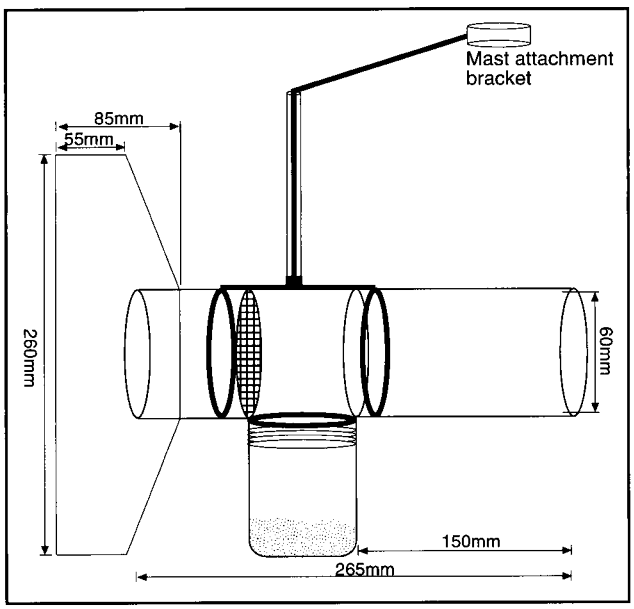

Figure 4. A schematic diagram of the Butterfield type passive sediment sampler

indicating that the length of tubing on the front of the traps allowed sufficient momentum extraction from the airstream to occur so that fines were not blown through the mesh filters.

No meteorological monitoring equipment was attached to the masts because of the ever-present risk of severe damage from sand blasting or loss due to flash floods, which are frequently experienced in the Southern Alps throughout spring. Instead, an automatic weather station (AWS) was located adjacent to the delta (Figure 1), which monitored standard meteorological parameters throughout the field study including wind speed, wind direction, air temperature, relative humidity and precipitation.

Attempts to sample sediment transported over the delta by surface creep and saltation using surface-based traps were abandoned due to the extremely dynamic nature of the study area, particularly the sandur. Both Leatherman type traps (Leatherman, 1976) and pit traps were observed to fill very quickly with sediment during moderate wind storms. The wind was removing sediment from the traps soon after their installation due to both rapid filling and the development of turbulent eddies within the top section of the traps. In addition, all traps were subjected to severe scour around their orifices and were considered inappropriate for this environment. Instead, samples collected by the Butterfield type traps attached to the masts at 0·5 m and 1 m above the surface were considered to be representative of the saltation cloud, as grains saltating over the coarse mixed sand and gravel deposits on which the mast was located, were typically observed to saltate to heights exceeding 1 m during wind erosion events. Saltation clouds of similar depth have been reported by McKenna Neuman (1993) in her review of aeolian processes in cold climates, where very high wind speeds and coarse-grained surface sediments promote the saltation of sand grains to heights exceeding 1 m (McKenna Neuman, 1990; Selby *et al*., 1973).

Grain size analysis

Samples of wind-blown sediment collected from the Godley River Delta by the Butterfield traps were oven-dried at 50°C for 48 h, after which all visible organic material was removed manually from each sample. Samples collected at 0·5 and 1 m above the deltaic surface, which were considered to be representative of the saltation cloud, were analysed by the Department of Geography's 2 m settling tube Rapid Sediment Analyzer (RSA) because of their significant sand size component, whereas those collected at 2 and 4 m above the surface were dry sieved at 63 μm. The larger sand-sized fraction of these samples was also analysed by the RSA and the silt/clay-sized fraction (<63 μm) underwent hydrometer analysis. This technique described by Reay (1971) is more suited to the analysis of fine particles and is comparable to the RSA method, as both techniques compute grain size statistics from particle settling velocities. Particles <63 μm were considered susceptible to medium- to long-term suspension and therefore subject to transportation many kilometres down valley during wind storms, but larger grains would settle out of the airstream much sooner. This approach therefore allowed for the separate analysis of dust particles considered able to affect Tekapo Village during northerly *foehn* wind storms.

The analysis of the silt/clay-sized grains also involved an assessment of grain roundness. Mazzullo *et al*. (1992) noted that aeolian transport results in a rapid downwind increase in grain roundness, which they suggested was due to an airstream's shape sorting ability and preferential transport of rounded grains. They also suggested that during saltation, rounded grains should be lifted higher above the surface. This is because the strength of the drag force exerted on the grain by an airstream increases with the roundness of a grain and is inversely proportional to the trajectory angle of the saltation and the height to which the grain is lifted above the bed. Consequently, a more rounded grain will be lifted higher above the bed than an angular grain of the same size and density under the same conditions (Mazzullo *et al*., 1992).

To test this hypothesis, six samples, each consisting of 100 silt/clay-sized grains (<63 μm), were analysed for grain roundness from sediment samples collected by the Butterfield traps over the Godley River Delta. This procedure used image processing computer software (Global Lab Image) to determine the roundness of silhouette images of individual grains, where the degree of roundness is indicated by a value between 0·0 and 1·0, 1·0 representing a circle. This approach required a magnified silhouette image of the grains to be displayed on a monitor, after which a grey shade was objectively determined to represent the grain's edge. This value was held constant throughout the analysis procedure, with grain roundness (GR) calculated by Equation 1:

$$GR = 4 \times \pi \times \text{area(pixels)}/\text{perimeter(pixels)}^2 \tag{1}$$

For consistency, the silhouette grain images were taken viewing the plane that included both the long and intermediate axes of the grains. To achieve this, each slide on which the grains lay was gently shaken as suggested in Lewis and McConchie (1994).

Table I. Grain size characteristics of saltation samples collected at 0·5 m, and meteorological conditions monitored during the sampling periods over the Godley River Delta, Lake Tekapo

Sampling site	Sampling period	Wind speed ($m\,s^{-1}$) mean/maximum	Average relative humidity (%)	Average air temperature (°C)	Sorting	Mean grain size (μm)	Median grain size (μm)	Skewness	Classification
Western Delta	31/10/91 to 16/11/91	10/16·9	49	9·8	Moderately well sorted	435	520	Finely skewed	Medium sand
Eastern Delta	31/10/91 to 16/11/91	10/16·9	49	9·8	Moderately well sorted	300	305	Finely skewed	Medium sand
Eastern Delta	8/8/92 to 2/10/92	10·2/16·2	43·7	8·8	Moderately well sorted	420	480	Finely skewed	Medium sand
Mid Delta	10/10/92 to 24/10/92	13·3/20·9	42·4	11·9	Moderately well sorted	320	370	Finely skewed	Medium sand
Western Delta	15/12/92 to 2/2/93	10·9/17·6	38·1	15·8	Moderately well sorted	325	340	Finely skewed	Medium sand

Results from grain size and shape analysis of wind-blown sediments

Results from the RSA analysis of saltation samples collected at 0·5 m above the deltaic surface are presented in Table I. Also shown are the average screen level air temperature, relative humidity and wind speed, and the maximum 20 min average wind speed for the sampling period as recorded by the AWS when the physical trigger conditions for aeolian grain transport were exceeded. The trigger conditions for aeolian grain transport over the fluvio-glacial deposits and the exposed delta were identified by McGowan (1994) to be a mean wind speed of 7·5 $m\,s^{-1}$ at 2·65 m above the surface, a relative humidity below 55 per cent and no precipitation.

Samples collected at 1 m above the surface during the same sampling periods displayed similar sedimentological characteristics, with mean grain sizes ranging from 255 to 420 μm, with all samples being moderately well sorted and finely skewed.

Samples collected at 2 and 4 m above the surface were sieved at 63 μm to determine the ratio of silt- and clay-sized particles to sand, as previously discussed. Approximately 60 to 65 per cent of sediment filtered from the airstream at 2 and 4 m above the deltaic surface during dust storm events was sand-sized material. The mean grain size of the sand-sized fraction of the samples was approximately 123 μm, while the silt/clay-sized material had a mean grain size of approximately 45 and 42 μm at 2 and 4 m, respectively. Both the sand- and silt/clay-sized fractions of the samples collected over the exposed delta displayed an expected reduction in median grain size (d_{50}) with height above the surface, which was best expressed by simple semi-logarithmic equations. For sand-sized particles, the reduction in median grain size was best expressed by Equation 2, while Equation 3 describes the reduction in the median grain size of the silt/clay-sized fraction of the plume within the first 4 m above the surface:

$$d_{50} = 143{\cdot}33 - 49{\cdot}83 \log_{10} z \tag{2}$$

$$d_{50} = 51{\cdot}25 - 9{\cdot}15 \log_{10} z \tag{3}$$

where z is the sampling height (m). Equations 2 and 3 produced R^2 values of 0·99 and 0·95, respectively, which was significant at 5 per cent.

Figure 5 presents the mean grain size plotted against height and derived from complete samples collected over the western part of the Godley River Delta using the Butterfield traps during a spring (31 October to 16 November 1991) and summer (15 December 1992 to 2 February 1993) sampling period. The most notable

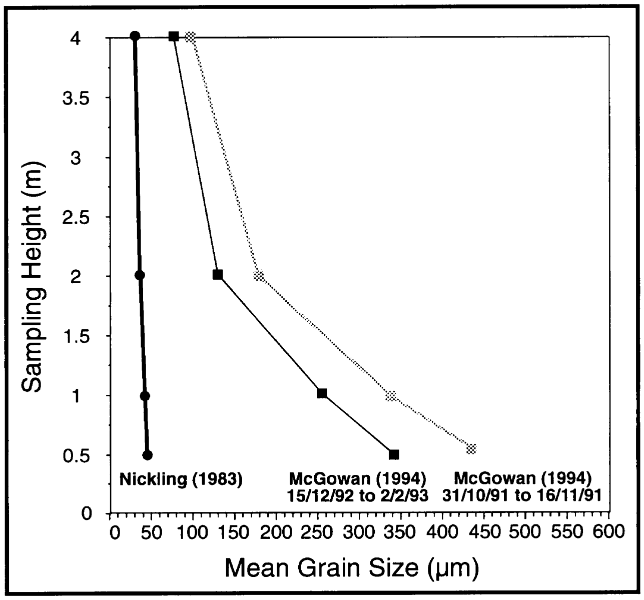

Figure 5. Two examples of the mean grain size of sediment filtered from the airstream over the Godley River Delta compared to observations made by Nickling (1983) on the Slims River Delta

feature in Figure 5 is that the ''dust'' plumes sampled over the Godley Delta appear to be strongly stratified, with a very coarse near-surface layer below 1·5 m. Above 2 m, the decrease in mean grain size with increasing height is much less pronounced, which may indicate the transition from saltation-dominated grain transport to suspension. In general, the samples collected over the Godley Delta displayed a much larger mean grain size than those collected by Nickling (1983) during 15 dust storms over the Slims River Delta. Secondly, samples collected over the Godley River Delta displayed a decrease in mean grain size with height, reflecting a semi-logarithmic relationship rather than the exponential relationship identified by Chepil and Woodruff (1957) and Nickling (1976, 1983).

Computer image analysis of fine grains (<63 µm) filtered from the airstream over the deltaic surface indicated the degree of grain roundness to increase with height above the surface. The mean roundness values for the two 100 grain samples collected at each of the three sampling heights above the delta were 0·73 (1 m), 0·76 (2 m) and 0·82 (4 m) respectively, thereby indicating that more rounded silt/clay-sized grains were carried higher into the airstream soon after entrainment.

DISCUSSION

Results from the grain size and shape analysis of wind-blown sediment collected over the Godley Delta identified several features not often discussed in the literature on aeolian grain transport. Of particular interest is the very large grain size of sediments travelling over the deltaic surface in the saltation cloud, which was approximately three to six times larger than those monitored by Nickling (1978, 1983) during dust storms on the Slims River Delta. This feature of aeolian grain transport over the Godley River Delta undoubtedly reflects, firstly, the significant power of *foehn* wind storms in the field area that initiate aeolian grain transport and, secondly, the importance of large cobble- and pebble-sized clasts in surface sediments which reflect saltating sand grains with minimal loss of kinetic energy. Such surfaces promote the saltation of large sand grains as they are thought to rebound from the surface at a significantly higher percentage of their initial impact velocity than the 60 per cent suggested by Willets and Rice (1985) for sand grains that impact on sand surfaces. As a result, the saltating sand grains appear to rebound from the predominantly pebble/cobble surface of the fluvio-glacial deposits in the lower Godley River Valley into zones of higher wind speed with each subsequent saltation. It is

therefore hypothesized that these saltating sand grains progressively acquire more momentum with each bounce into the airstream until an equilibrium state is reached between the height of each saltation, gravity and the subsequent extraction of momentum by the grains from the airstream, or until the grains impact on loose, fine-grained sediments. To the author's knowledge, no field or laboratory studies have been conducted that have examined in detail the physical characteristics of the saltation cloud over mixed sand and gravel surfaces, where observations made by his study indicate that the saltation cloud should extend much higher above the surface than is typically observed over sand (Butterfield, 1991; McKenna Neuman and Nickling, 1994).

The transportation of large sand grains by the airstream over the Godley Delta is also dependent on the velocity of the near-surface airstream. Mean 20 min wind speeds recorded by the AWS located adjacent to the Godley Delta during the monitoring periods discussed in this paper averaged between approximately 10 and 13 $m\,s^{-1}$, with maximum 20 min mean wind speeds ranging from 16 to 21 $m\,s^{-1}$ (Table I). Instantaneous maximum wind speeds (i.e. wind gusts during the sampling periods) were, however, much higher and typically exceeded 30 to 35 $m\,s^{-1}$. Such high wind speeds are considered of paramount importance in the initial entrainment process of large sand-sized grains (1–2 mm) such as those filtered from the saltation cloud by Butterfield type traps (McGowan, 1994). The wind speeds monitored by this study are considerably higher than those reported by Nickling (1976, 1983), who recorded mean wind speeds of only 4·5 to 10·2 $m\,s^{-1}$ at a similar height above the surface while sampling the saltation cloud. The high wind velocities monitored over the Godley River Delta during *foehn* wind storms result from the dynamic modification of the synoptic airstream by the Southern Alps. Topographic channelling of the airstream down the Godley River Valley enhances its velocity by compressing the near-surface streamlines, while atmospheric wave phenomena in the transalpine airflow also produce very strong near-surface winds, as discussed by Reid (1971) and McGowan and Sturman (1996).

Saltation samples collected at 0·5 m and 1 m above the surface of the Godley River Delta were positively skewed, indicating the dominance of a unidirectional transportation medium as suggested by Friedman (1961, 1967) and Williams (1964), in this case due to the downvalley *foehn* wind. Nickling (1983) recorded negative skewness in saltation samples on the Slims River Delta, which he attributed to the saltating grains receiving their momentum directly from the fluid pressure exerted on them by the airstream, rather than the ballistic impact of saltating grains. Consequently, the larger grains became entrained by the airstream in preference to fine grains because of the considerably larger surface area which they presented to the airstream. Over the Godley Delta, saltating sand grains appear to be the principal mechanism responsible for the entrainment of sediment through ballistic impact processes. As a result, the erosion of aerodynamically smooth surfaces consisting of silt/clay-sized material does occur, producing a fine-grained tail (positive skewness) in the sediment size distribution curve of the saltation samples collected above the surface.

Results from the computer image analysis of silt-sized grains filtered from the airstream indicate that more rounded grains are preferentially transported higher in the airstream than less rounded grains of similar size. This suggests that shape sorting by the airstream soon after entrainment results in rounded grains being carried higher above the surface, therefore entering regions of higher wind speed. Such grains should theoretically travel further from the entrainment zone than less rounded grains of the same size and density before being deposited. Consequently, the typically observed increase in grain roundness of aeolian deposits with increasing distance from the source area may reflect less the effects of abrasion of grains during transportation and more the effects of grain sorting by the airstream shortly after entrainment. For example, Willetts *et al*. (1982) observed that grain shape (roundness/sphericity) does have a substantial effect on both the transport rate of grains and their transportation paths in the first few centimetres above the surface. Such studies should be extended to examine the physical characteristics of grains carried much higher above the surface. For example, it is planned to collect fine-grained sediment for shape analysis at heights above 4 m in the Godley River Valley to determine to what height the increase in grain roundness occurs in dust plumes during blowing dust and dust storm events.

CONCLUSION

Topographically enhanced *foehn* winds were observed to initiate blowing dust and dust storms on the exposed Godley River Delta at the northern margin of Lake Tekapo, New Zealand. Grain size analysis of particulates

filtered from the airstream identified the mean and median grain size of the saltation cloud sampled at 0·5 and 1 m above the deltaic surface to be considerably larger than typically described in the international literature on aeolian grain transport. The saltation samples were moderately well sorted and positively skewed. Positive skewness reflects the dominance of a unidirectional grain-transporting medium – the northerly *foehn* airstream – and the ability of high energy saltating sand grains to eject fines into the airstream through ballistic impact processes from mostly aerodynamically smooth silt/clay deposits.

Approximately 60 to 65 per cent of sediment filtered from the airstream at 2 and 4 m above the surface during blowing dust and dust storm events was larger than 63 μm. This characteristic of the ‘‘dust’’ plume highlights the considerable turbulence that exists over the entrainment zone and the ability of such turbulence to support sand-sized grains in modified saltation/short-term suspension. Below 2 m, saltation of large sand grains over pebble- and cobble-sized alluvium appears to be the dominant transport mechanism over the exposed channels of the Godley Riverbed during low river flows.

Computer image analysis identified that an increase in grain roundness of silt-sized grains with increasing height above the surface did occur in the study area. This characteristic of aeolian grain transport has important implications with respect to the sedimentology of aeolian deposits, particularly the regularly observed increase in grain roundness in such deposits downwind of the source area. This feature was originally thought to result from the continued abrasion of grains during the transportation process, although results from this study indicate that shape sorting by the airstream shortly after entrainment is the likely cause of more rounded grains being carried aloft into layers of higher wind speed. As a result, these grains should theoretically travel further downwind than less rounded grains before deposition. Consequently, shape sorting by the airstream appears to contribute to the observed downstream increase in grain roundness associated with aeolian deposits.

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